

# Top Quark Properties

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Since its discovery in 1995 by the CDF and D0 collaborations at the Fermilab Tevatron collider, the top quark has undergone intensive studies. Besides the Tevatron experiments, with the start of the LHC in 2010 a top quark factory started its operation. It is now possible to measure top quark properties simultaneously at four different experiments, namely ATLAS and CMS at LHC and CDF and D0 at Tevatron. Having collected thousands of top quarks each, several top quark properties have been measured precisely, while others are being measured for the first time. In this article, recent measurements of top quark properties from ATLAS, CDF, CMS and D0 are presented, using up to  $5.4 \text{ fb}^{-1}$  of integrated luminosity at the Tevatron and  $1.1 \text{ fb}^{-1}$  at the LHC. In particular, measurements of the top quark mass, mass difference, forward backward charge asymmetry,  $t\bar{t}$  spin correlations, the ratio of branching fractions,  $W$  helicity, anomalous couplings, color flow and the search for flavor changing neutral currents are discussed.

## I. INTRODUCTION

The heaviest elementary particle known today is the top quark, with a mass of  $173.18 \pm 0.56(\text{stat}) \pm 0.76(\text{syst}) \text{ GeV}$  [1]. Due to its high mass and its short lifetime the top quark is believed to play a special role in electroweak symmetry breaking, serves as a window to physics beyond the standard model (SM), and provides a unique environment to study a bare quark. While the existence of the top quark was predicted by the SM, conclusive evidence is still required that the particle we observe is indeed the one predicted by theory. In order to use the top quark to search for new physics, it is therefore crucial to precisely determine the production rate and properties of top quarks and to confront the results with SM predictions. In particular, if top quark properties as for example the top width, the spin correlation or the forward backward charge asymmetry deviate from the SM prediction, it could indicate physics beyond the SM.

As of today, two colliders with high enough energy exist where top quarks can be produced. The first one is the Tevatron collider at Fermilab, which is a proton antiproton collider. During Run I of the Tevatron, lasting from 1992 to 1996,  $p\bar{p}$  collisions at 1.8 TeV collision energy were taking place. In 1995, the CDF and D0 experiments discovered the top quark with  $67 \text{ pb}^{-1}$  and  $50 \text{ pb}^{-1}$  of integrated luminosity, respectively [2, 3]. In 2001, Run II started with 1.96 TeV  $p\bar{p}$  collisions. Tevatron Run II lasted until September 30th, 2011, providing approximately  $10.5 \text{ fb}^{-1}$  of integrated luminosity per experiment. The second collider where top quarks can be produced [4, 5] is the Large Hadron Collider (LHC) at CERN, where protons are collided with protons at a center of mass energy of 7 TeV. LHC started operating in 2010, and has delivered already more than  $3 \text{ fb}^{-1}$  of collision data to the two multi-purpose detectors at LHC, AT-

LAS and CMS. Due to the high center of mass energy, the  $t\bar{t}$  production rate at LHC is about a factor of 20 larger than at the Tevatron, making the LHC a top quark factory [6, 7]. The large datasets at all four experiments, ATLAS, CDF, CMS and D0, enable us to measure top quark production and several top quark properties with high precision. In the following, recent studies of intrinsic top quark properties, top production and decay properties and direct searches for physics beyond the SM at ATLAS, CDF, CMS and D0 are presented, using up to  $5.4 \text{ fb}^{-1}$  of data for the Tevatron experiments and up to  $1.1 \text{ fb}^{-1}$  of data for the LHC experiments.

## II. TOP QUARK INTRINSIC PROPERTIES

Intrinsic properties of the top quark include its mass, its electric charge, its lifetime and its width. In this section recent results of the measurement of the top quark mass as well as the top antitop quark mass difference are discussed.

### A. Top Quark Mass

The mass of the top quark,  $m_t$ , is a free parameter of the SM. In addition to the necessity to determine this free parameter itself, the top quark mass together with the  $W$  boson mass yields a mass constraint on the so far undiscovered Higgs boson.

In order to measure the top quark mass as precisely as possible, several extraction techniques have been developed, which can be classified into template methods, ideogram methods and the Matrix Element method. The simplest method is the template method, where templates are constructed that depend on the top quark mass, which can then be fitted to

data. In the lepton+jets channel, where one of the  $W$  bosons from the top quark decays into a charged lepton and a neutrino that leaves the detector without interacting, and the other one into two quarks, the full event kinematics can be reconstructed using a kinematic fitter by constraining the invariant mass of the charged lepton and the neutrino to the known mass of the  $W$  boson. For dileptonic events, the two neutrinos in the final state cause underconstrained kinematics. In this case, additional integration over the unknown quantities is required, which is done using neutrino weighting or matrix weighting techniques. In the neutrino weighting technique, the pseudorapidities  $\eta$  [56] of the two neutrinos are sampled. For each choice of  $\eta$ , the kinematics of the event can be resolved with up to two solutions of the neutrino transverse momenta. These momenta are then used to calculate a weight for each solution and each assumed combination of  $\eta$  values, based on the agreement between the calculated neutrino transverse momenta and the measured value of the missing transverse energy. In the matrix weighting technique, a top quark mass dependent weight is calculated for each event by determining the consistency of the top-antitop quark momenta, using the assumed top quark mass, with the observed lepton and jet momenta and the missing transverse energy. In case of alljets events, where both  $W$  bosons from the top quark decay into a pair of quarks, the kinematics of the event is fully determined, but the challenge lies in finding the correct permutation of jets to match the top and antitop quarks.

The most precise technique to measure the top quark mass is the so-called Matrix Element (ME) method. For the ME method, the full kinematic information of each event is used, by calculating per-event signal probabilities  $P_{sig}(x; m_t)$  and background probabilities  $P_{bkg}$ , where  $x$  denotes the momenta of the final state partons. The probabilities are calculated by integrating over the leading order (LO) matrix element for the  $t\bar{t}$  production, folded with the parton distribution functions and transfer functions. The latter describe the transition of the parton momenta as needed for the matrix element into the measured momenta of the final state particles from the top quark decays. The measured top quark mass is then obtained by maximizing the likelihood of the product of these per-event probabilities. Since only leading order matrix elements are used and usually the background per-event probabilities get approximated by only using the matrix element for the largest background, the method needs to be calibrated using ensemble tests.

Finally, a third method that is an approximation of the ME method, is the so-called ideogram technique. Like in the ME technique, per-event probabilities are calculated, but with the modification that instead of matrix elements a kinematic fitter is used. The idea behind this method is to achieve a statistical uncertainty close to the ME method, but without the huge

computational effort as needed for the ME technique.

Independent of the method, the largest contribution to the systematic uncertainty on the top quark mass comes from the jet energy scale (JES). By constraining the invariant mass of the two jets coming from the  $W$  boson to the known  $W$  boson mass, the JES can be fitted in-situ in the lepton+jets and alljets channels, resulting in a reduced dependence of the top quark mass measurement on the JES uncertainty. In the dilepton final state the in-situ JES fit is not possible, but CDF recently performed a simultaneous measurement of  $m_t$  in the lepton+jets and dilepton final state, where the fitted JES from the hadronically decaying  $W$  boson in the lepton+jets channel was applied to the jets in the dilepton final state [8].

During the course of Run I and Run II of the Tevatron, all described techniques have been developed, refined and used to measure the top quark mass as precisely as possible. Recent measurements of  $m_t$  using template techniques are performed by CDF in the alljets ( $m_t = 172.5 \pm 2.0(\text{stat} + \text{syst})$  GeV [9] using  $5.8 \text{ fb}^{-1}$ ), dilepton ( $m_t = 170.3 \pm 3.7(\text{stat} + \text{syst})$  GeV [8] using  $5.6 \text{ fb}^{-1}$ ) and  $\cancel{E}_T$ +jets ( $m_t = 172.3 \pm 2.6(\text{stat} + \text{syst})$  GeV [10] using  $5.7 \text{ fb}^{-1}$ ) channels, by the ATLAS collaboration in the lepton+jets final state ( $m_t = 175.9 \pm 0.9(\text{stat}) \pm 2.7(\text{syst})$  GeV [11] using  $0.7 \text{ fb}^{-1}$ ) and by CMS in the dileptonic final state using the matrix weighting technique ( $m_t = 175.5 \pm 4.6(\text{stat}) \pm 4.6(\text{syst})$  GeV [12] using  $36 \text{ pb}^{-1}$ ). Using the ideogram method, recently CMS measured  $m_t = 173.1 \pm 2.1(\text{stat})^{+2.8}_{-2.5}(\text{syst})$  GeV in the lepton+jets final state [13] with  $36 \text{ pb}^{-1}$  of data. New results using the ME method are a measurement from D0 in the dileptonic final state ( $m_t = 174.0 \pm 3.0(\text{stat} + \text{syst})$  GeV [14] using  $5.4 \text{ fb}^{-1}$ ) and the lepton+jets final state ( $m_t = 174.9 \pm 1.5(\text{stat} + \text{syst})$  GeV [15]) as well as a measurement in the lepton+jets channel by CDF ( $m_t = 173.0 \pm 1.2(\text{stat} + \text{syst})$  GeV [16] using  $5.6 \text{ fb}^{-1}$ ), the latter being the single most precise measurement of the top quark mass to date.

A combination of all recent as well as older top quark mass measurements using the various measurement techniques from Run I and Run II of the Tevatron has been performed, yielding  $m_t = 173.18 \pm 0.56(\text{stat}) \pm 0.76(\text{syst})$  GeV [1]. A precision of 0.6% is achieved on the top quark mass measurement, which is dominated by systematic uncertainties. The main sources of systematic uncertainties arise from uncertainties due to the differences of the JES for different jet flavors and uncertainties on the signal modeling. The latter include initial and final state radiation, color reconnections, and next-to-leading order (NLO) versus LO Monte Carlo (MC) generators, from uncertainties due to the in-situ fit of the jet energy scale and related residual dependences of JES on jet  $p_T$  and  $\eta$ . Figure 1 (left) shows the different Tevatron top quark mass measurements and the combination.

All direct top quark mass measurements rely on MC simulations for the template construction or calibration of the method. These simulations are performed in LO quantum chromodynamics (QCD), with higher order effects simulated through parton showers at modified leading logarithms (LL) level. Since the top quark mass is a convention-dependent parameter beyond LO QCD, it is important to know how to interpret the result of the direct measurement in terms of renormalization conventions. Currently, it is still under theoretical investigations how the measured top quark mass from MC and the top quark pole or  $\overline{MS}$  mass are related. Recently, the D0 Collaboration has determined the top quark mass from the measurement of the  $t\bar{t}$  cross section by comparing the measured  $t\bar{t}$  cross section to inclusive cross section calculations versus top quark mass, allowing an unambiguous interpretation in the pole or  $\overline{MS}$  mass scheme [18]. Using the pole mass for inclusive cross section calculations D0 extracted a pole mass of, for example,  $m_t = 167.5^{+5.2}_{-4.7}$  GeV for the cross section calculation from Ref. [17]. Doing the same extraction again but with a calculation in the  $\overline{MS}$  mass scheme yields about 7 GeV smaller values for  $m_t$ . Recently, ATLAS [19] and CMS [20] also performed a top quark mass from cross section extraction in the pole mass scheme, which yields consistent results with the D0 values.

### B. Top Antitop Mass Difference

The direct top quark mass measurements assume the top and the antitop quark mass to be identical, as required by the SM. If particles and their corresponding anti-particles would not have equal masses, this would indicate CPT violation. By dropping the assumption of equal top and antitop quark masses, the CDF, CMS and D0 collaborations have performed measurements of the top antitop quark mass difference. The first measurement of the mass difference between a bare quark and its antiquark was performed by the D0 collaboration using the ME method, by extending the event probabilities  $P_{sig}(x; m_t)$  to  $P_{sig}(x; m_t, m_{\bar{t}})$  using  $1 \text{ fb}^{-1}$  of data in the lepton+jets final state [21]. D0 repeated the measurement using  $3.6 \text{ fb}^{-1}$  of data, resulting in  $m_t - m_{\bar{t}} = 0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst}) \text{ GeV}$  [22], which is consistent with the SM. The CDF collaboration performed the mass difference measurement using a template technique in the lepton+jets channel using  $5.6 \text{ fb}^{-1}$  of data, resulting in  $m_t - m_{\bar{t}} = -3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst}) \text{ GeV}$  [23]. The most precise top antitop quark mass difference measurement to date was recently performed by the CMS collaboration by extending the top mass measurement in the muon+jets channel using the ideogram technique. In particular, the top quark mass is measured separately in sam-

ples with positively and negatively charged muons, and the resulting top mass values are subtracted. Using  $1.09 \text{ fb}^{-1}$  of data, the CMS result is  $m_t - m_{\bar{t}} = 1.2 \pm 1.2(\text{stat}) \pm 0.5(\text{syst}) \text{ GeV}$  [24]. All top antitop mass difference measurements are still dominated by statistical uncertainties.

## III. TOP QUARK PRODUCTION PROPERTIES

In this section two measurements probing the properties of the top quark production are discussed, namely the measurement of the  $t\bar{t}$  forward backward charge asymmetry and the  $t\bar{t}$  spin correlations. The latter not only probes the production but the full chain of  $t\bar{t}$  production and decay.

### A. $t\bar{t}$ Forward Backward Charge Asymmetry

At LO QCD, the production of top antitop quark pairs is forward backward symmetric in quark antiquark annihilation processes. However, at higher order interferences between different diagrams cause a preferred direction of the top and antitop quarks and therefore an asymmetry. In particular, at NLO, the leading contribution is from the the interference between tree level and box diagrams, which yield a positive asymmetry, where the top quark is preferentially emitted in the direction of the incoming quark. A deviation from the SM prediction could indicate physics beyond the SM. For example, axial currents could contribute to the s-channel production and change the asymmetry.

Due to the Tevatron being a  $p\bar{p}$  collider, where the  $t\bar{t}$  production is dominated by the interaction of a valence quark and a valence antiquark and therefore the (anti)quark direction almost always coincides with the direction of the incoming (anti)proton, the measurement of the forward backward charge asymmetry at the Tevatron is conceptionally easy. At the LHC, which is a  $pp$  collider, two factors result in a more challenging measurement of the asymmetry as well as in a smaller theory prediction: At 7 TeV, gluon-gluon fusion dominates the  $t\bar{t}$  production (which contributes about 85% to the  $t\bar{t}$  production), which does not cause an asymmetry, and the direction of the incoming quark is unknown. Therefore, the strategies to measure the asymmetry at the two colliders are different.

At CDF and D0, the asymmetry is defined in terms of the difference between the rapidity of the top and antitop quarks,  $\Delta y$ . The assignment of the final state particles to top and antitop quarks is determined by applying kinematic fitting techniques to the fully reconstructed  $t\bar{t}$  events in the lepton+jets and dilepton final states. The charge of the lepton(s) is used

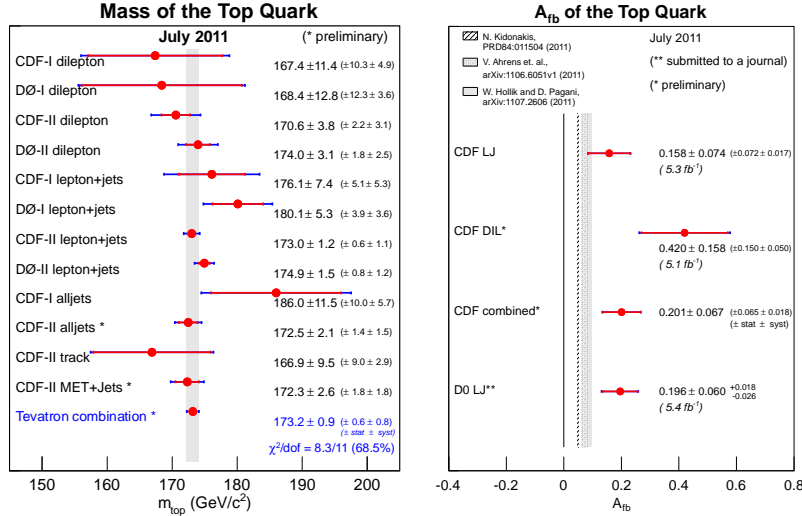


FIG. 1: Left: Tevatron top quark mass measurements in the different final states during Run I and Run II and their combination [1]. Right: Measurements of the forward backward charge asymmetry  $A_{fb}$  at the Tevatron [27].

to determine which combination of final state objects belongs to the top and which to the antitop quark. The asymmetry is then defined as  $A_{fb} = [N(\Delta y > 0) - N(\Delta y < 0)]/[N(\Delta y > 0) + N(\Delta y < 0)]$ , where  $N(\Delta y > 0)$  and  $N(\Delta y < 0)$  are the number of events with rapidity difference larger and smaller zero, respectively. Alternatively, the asymmetry can be extracted from the rapidity of the lepton(s) only, which has the advantages that no complete reconstruction of the top and antitop quarks and their decays is required and that the directions of the charged leptons can be measured with good resolution. The disadvantage is that the direction of the lepton is not fully correlated to the top quark direction, resulting in a loss of sensitivity. In order to compare to theory predictions, the measured  $t\bar{t}$  forward backward asymmetries are corrected for acceptance and resolution effects to obtain the inclusive generated asymmetry. The correction is done using a  $4 \times 4$  matrix-inversion at CDF and with regularized unfolding at DØ.

At ATLAS and CMS, the asymmetry definition used for the recent measurements relies on the fact that  $t\bar{t}$  production via  $q\bar{q}$  annihilation is dominated by initial valence quarks with large momentum fractions and initial antiquarks from the sea with smaller momentum fractions. An asymmetry with the top quark being preferentially emitted in the direction of the incoming quark therefore has the effect that the top quarks has a wider rapidity distribution than the antitop quarks, which are more central. Accordingly, the asymmetry is measured using the definition  $A_C = [N(\Delta|y| > 0) - N(\Delta|y| < 0)]/[N(\Delta|y| > 0) + N(\Delta|y| < 0)]$ , with  $\Delta|y|$  being the difference of the absolute rapidity of the top and antitop quark.

The latest measurements of the asymmetry at the Tevatron were performed in the lepton+jets chan-

nel at CDF and DØ, and in the dilepton final state by CDF. The CDF collaboration measured an inclusive generated asymmetry of  $A_{fb} = 0.158 \pm 0.074$  using  $5.3 \text{ fb}^{-1}$  of data in the lepton+jets channel [25], and  $A_{fb} = 0.420 \pm 0.158$  in the dilepton final state with  $5.1 \text{ fb}^{-1}$  of data [26]. The combination of these two measurements results in  $A_{fb} = 0.201 \pm 0.067$  [27]. The DØ measurement with  $5.4 \text{ fb}^{-1}$  of data in the lepton+jets channel yields  $A_{fb} = 0.196 \pm 0.060(\text{stat})^{+0.018}_{-0.026}(\text{syst})$  [28]. A summary of these results and the theory predictions is shown in Fig. 1 (right). All results are still dominated by statistical uncertainties. Comparing the measurement to various theoretical predictions [29] and the prediction of MC@NLO [30] MC shows about a two sigma deviation towards higher values of the measurements from the prediction. So far it is not clear whether this deviation comes from new physics contributions or modeling of the SM or anything else, causing a strong interest in the asymmetry measurements. Various tests to check the MC modeling have been performed, as for example a test performed by the DØ collaboration to check the sensitivity to the modeling of the transverse momentum of the  $t\bar{t}$  system,  $p_T(t\bar{t})$ . This test showed that the asymmetry predicted by several MC generators is indeed sensitive to  $p_T(t\bar{t})$ , which will require further investigations in the future.

Recently, the ATLAS and CMS collaborations performed their first measurement of  $A_C$  in the lepton+jets final state. Using  $0.7 \text{ fb}^{-1}$ , the ATLAS collaboration measured  $A_C = -0.024 \pm 0.016(\text{stat}) \pm 0.023(\text{syst})$ , to be compared to a theory prediction of 0.6% [31]. The CMS collaboration used the pseudorapidity instead of the rapidity for the measurement of  $A_C$ , resulting in  $A_C^{\eta} = -0.016 \pm$

$0.030(\text{stat})_{-0.019}^{+0.010}(\text{syst})$  using  $1.09 \text{ fb}^{-1}$  of data [32]. Neither result shows a significant deviation from the SM predictions.

Besides the inclusive measurement, it is interesting to investigate the dependence of the asymmetry on various variables, as for example the rapidity or the invariant mass of the top antitop quarks,  $m_{t\bar{t}}$ . CDF and D0 investigated the  $m_{t\bar{t}}$  dependence by measuring  $A_{fb}$  for regions of  $m_{t\bar{t}} < 450 \text{ GeV}$  and  $m_{t\bar{t}} > 450 \text{ GeV}$ . While in D0 data, no significant dependence was observed [28], an excess of about three sigma standard deviation from the MC@NLO prediction was observed by the CDF collaboration for  $m_{t\bar{t}} > 450 \text{ GeV}$  [25]. The CMS collaboration also checked the dependence on  $m_{t\bar{t}}$ , and no significant dependence showed up in the CMS data [32].

## B. $t\bar{t}$ Spin Correlations

While the top quarks are produced unpolarized at hadron colliders, the spins of the top and antitop quarks are expected to be correlated. Due to the short lifetime of the top quark, which is shorter than the time scale for hadronization, the information of the top quark's spin is preserved in its decay products, enabling the measurement of the spin correlation of the top and antitop quark in  $t\bar{t}$  events. Recently, two different methods have been explored to measure  $t\bar{t}$  spin correlations, namely a template based method relying on angular distributions, and a matrix element based method.

Template based methods were used by the ATLAS, CDF and D0 collaborations. At D0 and CDF, the measurements are based on the fact that the doubly differential cross section,  $1/\sigma \times d^2\sigma/(d\cos\theta_1 d\cos\theta_2)$  can be written as  $1/4 \times (1 - C \cos\theta_1 \cos\theta_2)$ , where  $C$  is the spin correlation strength, and  $\theta_1$  ( $\theta_2$ ) is the angle of the down-type fermion from the  $W^+$  ( $W^-$ ) boson or top (antitop) quark decay in the top (antitop) quark rest frame with respect to a quantization axis. Common choices are the helicity basis, where the quantization axis is the flight direction of the top (antitop) quark in the  $t\bar{t}$  rest frame, and the beam basis, where the quantization axis is the beam axis. A third common choice of quantization axis is the off-diagonal basis, which yields the helicity axis for ultra-high energy and the beam axis at threshold. The SM prediction for the spin correlation strength  $C$  depends on the collision energy and the choice of quantization axis, and is  $C = 0.78$  for the Tevatron in the beam basis at NLO [33]. The spin correlation strength  $C$  can be presented as the number of events where top and antitop have the same spin direction minus the number of events with opposite spin direction, normalized to the total number of  $t\bar{t}$  events, multiplied with a factor representing the analyzing power of the down-type fermion used to calculate the angles. The

latter factor is one for leptons and down-type quarks from the  $W$  boson decay at LO QCD, but smaller for up-type quarks and the  $b$ -quark from top quark decay. Since it is experimentally challenging to distinguish up-type from down-type quarks, the dilepton channel is best to perform spin correlation measurements. The CDF and D0 collaborations performed an analysis of the spin correlation strength  $C$  by fitting templates for  $C = 0$  and the SM value of  $C$  of the distribution  $\cos\theta_1 \cos\theta_2$  to data. Using  $2.8 \text{ fb}^{-1}$  at CDF and  $5.4 \text{ fb}^{-1}$  at D0, the measurement of  $C$  in the beam basis yields  $C = 0.32_{-0.78}^{+0.55}(\text{stat} + \text{syst})$  [34] and  $C = 0.10 \pm 0.45(\text{stat} + \text{syst})$  [35], in agreement with SM prediction. Similar to these two analyses in the dilepton final state, CDF performed the first extraction of  $t\bar{t}$  spin correlations by fitting templates of equal and opposite  $t\bar{t}$  helicity to data. The measured quantity is then translated into  $C$ . Using a dataset of  $4.3 \text{ fb}^{-1}$ , CDF measured  $C = 0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$  in the beam basis [36].

Recently, the D0 collaboration explored a different method to measure  $t\bar{t}$  spin correlation, where per-event signal probabilities  $P_{sig}(H)$  are calculated using matrix elements that include spin correlations ( $H = c$ ) and do not include spin correlations ( $H = u$ ), and are translated into a discriminant  $R = P_{sig}(H = c)/[P_{sig}(H = c) + P_{sig}(H = u)]$  [37]. Applying this technique to the same D0 dataset of  $5.4 \text{ fb}^{-1}$  of dilepton events as for the template based method, results in a 30% improved sensitivity, yielding  $C = 0.57 \pm 0.31(\text{stat} + \text{syst})$  [38]. The matrix element-based method has been extended to the lepton+jets final state using  $5.3 \text{ fb}^{-1}$  of D0 data, and by combining the measurement in dilepton and lepton+jets events first evidence for spin correlation was reported recently [39]. All Tevatron measurements are in agreement with the NLO SM prediction, and all are still limited by statistics.

While at the Tevatron  $q\bar{q}$  production at threshold dominates, the dominant  $t\bar{t}$  production at LHC is via gluon-gluon fusion. In a recent theory article [40] it was suggested that the  $t\bar{t}$  production at the LHC at low parton collision energy is dominated by fusion of like helicity gluons. A simple variable was proposed, which is the difference in azimuthal angle of the two leptons in the lab frame,  $\Delta\phi$ , in dileptonic final states. In contrast to the discussed template based measurements at CDF and D0, no full reconstruction of the  $t\bar{t}$  system is required and  $\Delta\phi$  can therefore be precisely measured. The ATLAS collaboration performed the first measurement of  $t\bar{t}$  spin correlation at the LHC using the variable  $\Delta\phi$ , which yields  $C_{heli} = 0.34_{-0.11}^{+0.15}(\text{stat} + \text{syst})$  in the helicity basis using  $0.7 \text{ fb}^{-1}$  of data [41]. This is in agreement with the NLO SM prediction of  $C_{heli}^{theo} = 0.32$ . The measurement by ATLAS is dominated by systematic uncertainties due to the signal modeling, mainly the modeling of initial and final state radiation.

#### IV. TOP QUARK DECAY PROPERTIES

Since physics beyond the SM could also show up in top quark decays, it is important to study top quark decay properties, as for example the ratio of branching fractions, the  $W$  helicity or anomalous couplings. Recent studies of these properties are presented in this section.

##### A. Ratio of Branching Fractions

In the SM, the top quark decays to a  $W$  boson and a  $b$ -quark with almost 100% probability. In the measurement of the ratio of branching fractions  $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$ , with  $q = b, s, d$ , the possibility is studied that the quark from the top quark decay can be a light down-type quark. Physics beyond the SM or a fourth generation of quarks could cause  $R$  to be below its SM value of one. In a new measurement of  $R$  by the D0 collaboration, using  $5.4 \text{ fb}^{-1}$  of data, the ratio of branching fractions has been measured in the dilepton and lepton+jets final states [42]. In the lepton+jets channel, the distribution of events with 0, 1 or  $\geq 2$  identified  $b$ -jets is used to discriminate  $R$ , while in the dilepton channel the distribution of the output of the  $NN$   $b$ -tagging algorithm [43] is analysed. To reduce the influence of systematic uncertainties that change the normalization of signal and background contributions, the  $t\bar{t}$  cross section is fitted simultaneously with  $R$ , resulting in  $R = 0.90 \pm 0.04(\text{stat} + \text{syst})$ , which is the most precise determination of  $R$  to date. Lower limits on  $|V_{tb}|$  assuming unitarity of the  $3 \times 3$  CKM matrix can then be extracted from  $R$ , resulting in  $|V_{tb}| = 0.95 \pm 0.02(\text{stat} + \text{syst})$ . The measurement is limited by systematic uncertainties, with the main source coming from uncertainties on  $b$ -jet identification. The measured value of  $R$  shows about a two sigma standard deviation from the SM.

##### B. $W$ Helicity and Anomalous Couplings

The relative orientation of the spin of the  $b$ -quark and the  $W$  boson from the top quark decay are constrained in the SM by the fact that  $W$  bosons couple purely left-handed to fermions. The fractions of negative ( $f_-$ ), zero ( $f_0$ ) and positive ( $f_+$ ) helicity of the  $W$  boson are predicted to be  $f_- = 0.685 \pm 0.005$ ,  $f_0 = 0.311 \pm 0.005$  and  $f_+ = 0.0017 \pm 0.0001$  at next-to-next-to-leading order (NNLO) QCD [44]. Similar to the measurement of the top quark mass and  $t\bar{t}$  spin correlations, various methods can be used to measure the  $W$  boson helicity fractions, namely a template based method and the ME technique. In the template method, the angle  $\theta^*$  between the down-type decay product of the  $W$  boson and the top quark in

the  $W$  boson rest frame is measured, which differs for the three possible helicity fractions, and distributions of the cosine of this angle are fitted to data. To keep the analysis as model-independent as possible, the fractions  $f_0$  and  $f_+$  are fitted simultaneously, only constraining the sum of all three fractions to be one. The CDF collaboration also uses the ME method to measure the  $W$  boson helicity, where the per-event signal probabilities  $P_{sig}$  are calculated as function of  $f_0$  and  $f_+$  instead of  $m_t$ , with the latter fixed to 175 GeV. Recently, a combination of a D0 measurement in the dilepton and lepton+jets channel using  $5.4 \text{ fb}^{-1}$ , a CDF measurement in the lepton+jets final state using  $2.7 \text{ fb}^{-1}$ , and a CDF analysis in the dilepton final state using  $5.1 \text{ fb}^{-1}$  has been performed [45]. Using the model independent approach, the combination yields  $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$  and  $f_+ = -0.039 \pm 0.034(\text{stat}) \pm 0.030(\text{syst})$ , in good agreement with the SM prediction. Furthermore, the CDF collaboration updated their measurement in the dilepton final state using  $5.1 \text{ fb}^{-1}$ , improving the sensitivity by applying  $b$ -jet identification. This result is not yet included in the Tevatron combination and yields  $f_0 = 0.71^{+0.18}_{-0.17}(\text{stat}) \pm 0.06(\text{syst})$  and  $f_+ = -0.07 \pm 0.09(\text{stat}) \pm 0.04(\text{syst})$  [46].

Using the template fit of the  $\cos\theta^*$  distributions, the ATLAS collaboration performed the first measurement of the  $W$  helicity fractions at the LHC. In the lepton+jets channel, the model independent fit is applied, resulting in  $f_0 = 0.57 \pm 0.07(\text{stat}) \pm 0.09(\text{syst})$  and  $f_+ = 0.09 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})$  with  $0.70 \text{ fb}^{-1}$  of data [47], where the dominant systematic uncertainties are from signal modeling and modeling of initial and final state radiation. For the dilepton final state the data sample was too small to perform the model independent approach, and instead  $f_+$  is fixed to zero and  $f_0$  is fitted. The dilepton and lepton+jets combined measurement with  $f_+ = 0$  yields  $f_0 = 0.75 \pm 0.08(\text{stat} + \text{syst})$ , which is consistent with the SM prediction.

Using the measurements of the  $W$  helicity fractions, or single top events, constraints on anomalous couplings of the  $Wtb$  vertex can be extracted. In the SM only left-handed vector couplings ( $V_L$ ) are allowed, while a more general  $Wtb$ -Lagrangian could allow right-handed vector ( $V_R$ ), left-handed tensor ( $g_L$ ) or right-handed tensor ( $g_R$ ) couplings. The ATLAS collaboration extracted limits on  $V_R$ ,  $g_L$  and  $g_R$  using the  $W$  helicity measurement [47], while the D0 collaboration extracted limits on these couplings using the selection for single top events [48]. A previous analysis performed by the D0 collaboration on up to  $2.7 \text{ fb}^{-1}$  of data showed that the combination of  $W$  helicity and single top measurements improves the sensitivity to all three anomalous couplings wrt. the single measurements [49].

## V. OTHER TOP QUARK STUDIES AND SEARCHES

Precision measurements of top quark properties and their comparison to SM predictions are crucial to study the nature of the particle discovered in 1995 and believed to be the top quark. Additionally, direct searches in the top quark sector could reveal physics beyond the SM or an unexpected behaviour of the top quark. In the following, an example of a study of color flow in  $t\bar{t}$  events and a search for flavor changing neutral currents (FCNC) are presented.

### A. Color Flow in $t\bar{t}$ Events

In QCD, color charge is a conserved quantity, causing two final-state particles on the same color-flow line to be color connected to each other. In a recent paper [50], a tool called jet pull, which is related to the jet energy pattern in the  $\eta - \phi$  plane, has been suggested to measure color flow between a jet pair and distinguish color-octet from color-singlet states. For jets from color singlet states, such as a  $b$ -jet pair from Higgs boson decay, the pulls of the jets tend to point towards each other, while for a  $b$ -jet pair from a color-octet gluon the pulls would point in opposite directions along the collision axis. Before such a tool can be applied to new physics searches, it has to be studied in a known environment, as for example in semileptonic  $t\bar{t}$  events, where the two light jets from the  $W$  boson decay are expected to come from a color-singlet. Recently, the D0 collaboration performed the first study of color flow using the jet pull variable in  $t\bar{t}$  events. Using  $5.3 \text{ fb}^{-1}$  of data, a SM  $t\bar{t}$  MC with a color-singlet  $W$  boson has been compared to a  $t\bar{t}$  sample with a hypothetical, hadronically decaying, color-octet “W” boson. The jet pull variable has been applied to extract the fraction  $f$  of color-singlet hadronic  $W$  boson decays, resulting in  $f = 0.56 \pm 0.38(\text{stat} + \text{syst}) \pm 0.19(\text{MCstat})$  [51], with an expected 99% confidence level exclusion of the color-octet “W” boson. This study is still dominated by the statistics of the analyzed data sample.

### B. Search for Flavor Changing Neutral Currents

Transitions between quarks of the same electric charge but different flavors could occur if FCNCs exist. In the SM, FCNC are suppressed. Therefore, observation of FCNC would indicate physics beyond the SM, as for example supersymmetric models or quark compositeness. At the Tevatron, various searches for FCNC in the top sector have been performed, for example searches for the decay  $t \rightarrow gq$ , with  $q = c, u$  in single top events [52] and searches for  $t \rightarrow Zq$  in  $t\bar{t}$

events. For the latter, a search in dileptonic  $t\bar{t}$  events has been performed by the CDF collaboration, using  $1.9 \text{ fb}^{-1}$  of data [53], as well as a recent search by the D0 collaboration using trilepton final states [54]. For the search by D0 a  $t\bar{t}$  sample of  $4.1 \text{ fb}^{-1}$  of integrated luminosity has been used, where at least one of the top quarks decays to a  $Z$  boson and a light quark, with the  $W$  boson and  $Z$  boson(s) decaying leptonically, resulting in at least three leptons in the final state. To increase the sensitivity, distributions sensitive to FCNC, like the scalar sum of the transverse momenta of all leptons, jets, and  $\cancel{E}_T$ , are included in the limit setting procedure. This search yields the world’s best limits on FCNC to date, of  $B(t \rightarrow Zq) < 3.2\%$  at 95% confidence level.

Using  $35 \text{ pb}^{-1}$  of data, ATLAS performed a search similar to the trilepton search by D0, but with counting events only [55], resulting in  $B(t \rightarrow Zq) < 17\%$  at 95% confidence level. Furthermore, ATLAS searched for anomalous single top production through FCNC using the same dataset. Neural networks are used to separate  $gq \rightarrow t$  signal from background, resulting in upper limits on the cross section  $\sigma_{gq \rightarrow t} \times B(t \rightarrow bW)$  of  $17.3 \text{ pb}$  at 95% confidence level.

## VI. CONCLUSION AND OUTLOOK

A collection of the most recent measurements of top quark properties at the ATLAS, CDF, CMS, and D0 collaborations has been discussed in this presentation. About  $10.5 \text{ fb}^{-1}$  of data have been collected by the CDF and D0 collaborations in Run II of the Tevatron, which ended on September 30th, 2011. Only about half of this dataset has been used so far for top quark studies. The Tevatron experiments plan to analyse the final dataset for those measurement which are complementary or competitive to the LHC results, including the top quark mass measurement, the measurement of the forward-backward charge asymmetry and  $t\bar{t}$  spin correlations. With the start of the LHC in 2010, a top quark factory was opened. Having collected more than  $3 \text{ fb}^{-1}$  already, the comparison of top quark measurements to theory predictions reaches new levels of precision. Given the top quark’s special role in particle physics, it is and will stay an interesting particle to study at all four experiments.

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